Department of Mechanical and Aerospace Engineering

A study into the optimisation and calculation of electrical losses in renewable energy generation

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Abstract

This project will investigate the main causes of electrical losses in renewable energy generation.

The financial backers of many of the renewable projects being constructed today are primarily concerned with achieving maximum profitability for their clients. One of the key losses of revenue for a renewable energy project is ongoing losses from the electrical components. It is therefore essential that we can accurately predict electrical losses before investment. Investors need accurate, bankable data pre construction and during site acquisition phases.

Firstly, a review of the losses attributed to the electrical technologies involved in renewable energy generation will be conducted. This will involve performing an analysis of empirical data from a variety renewable energy projects.

This data will then be used to construct tool for quickly and accurately predicting losses in future projects thus giving potential investors bankable data for their investments.

Acknowledgements

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And finally to Rebecca. This one is for you.

Contents

List of Figures

List of Tables

Abbreviations and Acronyms

Abbreviation or Term	Definition
AC	Alternating Current
Ampacity	Electrical current carrying capacity
Capex	Capital Expenditure
DC	Direct Current
DNO	Distribution Network Owner
DRS	Dynamic Rating System
DTS	Distributed Temperature Sensing
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HV/MV/LV	High Voltage / Medium Voltage
LTDS	Long Term Development Statement
MPPT	Maximum power point tracking
MVA	Mega Volt Amperes
MVAr	Mega Volt Amperes reactive
MW	Mega Watts
OFTO	Offshore Transmission Owner
OHL	Overhead Line
ONAN	Oil Natural Air Natural
Opex	Operational Expenditure
OTDR	Optical Time Domain Reflectometry
OWF	Offshore Wind Farm
RTTR	Real Time Thermal Rating
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator
WTG	Wind Turbine Generator
XLPE	Cross Linked Poly Ethylene

1. Introduction

1.1. Background

The purpose of this thesis is to investigate the electrical losses in renewable energy generation across several renewable generation technologies. Only the losses encountered between point of generation and the metering connection point will be considered as these are key to the bankable data which investors and developers require to make informed financial decisions. These investors and developers use renewable energy consultancies such as SgurrEnergy to provide the technical expertise to back up their financial knowledge and allow them to make informed choices about their investments.

Renewable energy generation projects are generally financed through a project finance approach. Equity and project finance investment groups typically conduct a project evaluation covering the legal aspects, permits, contracts, technical and financial aspects. These are evaluated prior to achieving the projects financial close. Projects are evaluated through Legal, Insurance and Technical due diligence processes. The technical due diligence process concentrates on the following aspects:

- Sizing of the generation plant (MW).
- Physical layout of the site.
- Electrical design layout and sizing.
- Technology review of the major components.
- Energy yield assesments.
- Contract assessments
- Financial model assumptions

SgurrEnergy perform many professional services for investors and developers throughout the lifecycle of a renewable project. Some of these services include performing this due diligence and energy yield analysis.

SgurrEnergy and especially the electrical department are frequently asked about the electrical losses expected from a renewable energy generation project. To ensure good value for clients the electrical team requires an easy to use and accurate loss prediction method.

1.2. Objectives

The objective of this thesis is to undertake an analysis of the electrical losses encountered in renewable energy generation and create an accurate prediction tool that can be used to inform clients and investors. This thesis will document the process that will enable the electrical team to provide bankable information on electrical losses quickly and accurately while providing good value for both SgurrEnergy and the Client. These loss calculations will then be able to be integrated into due diligence or energy yield reports for other departments for submission to the Client.

Loss data and energy yields from existing renewable energy generation projects will be collected and used to test the validity of the loss prediction tool.

The tool will be constructed in excel and will be an easy to use interface with multiple input options. These will include Cable type, transformers and solar components such as inverters and combiner boxes. Different renewable technologies such as solar photovoltaic, onshore and offshore wind will be included in the loss calculation tool as these make up the bulk of SgurrEnergy's current portfolio.

1.3. Scope

The tool will be constructed upon mathematical models taken from first principle electrical loss calculations. The tool will have to be accurate across various different parameters for it to be admissible as bankable data for investors and developers. Only components that contribute to a significant electrical loss will be factored in to the model.

This thesis takes loss data from established projects in several worldwide locations within SgurrEnergy's extensive portfolio. The generation voltages vary as do the generating technologies and size and location of the projects.

1.4. Methodology

A literature review was conducted on relevant published articles, working groups, presentations, brochures, equipment specifications and industry papers. These are to be reviewed to give an understanding of the past and recent developments in the field of electrical losses.

An indicative loss calculation model will be constructed in Microsoft Excel and is aimed at providing an illustrative approach to the electrical losses expected over a range of renewable generation options.

Actual loss data from renewable generation plants within the SgurrEnergy portfolio will be analysed and compared to the tool results to ensure accuracy across all the renewable technologies.

A case study on a renewable energy generator will be conducted and its actual measured electrical output compared to the calculated output determined by the loss calculation tool.

This will give an indication of the tools accuracy.

2. Technology

Renewable energy generation comes in many forms and Scotland is lucky to be situated geographically to take advantage of all of them with the exception of Solar which would be better implemented in sunnier climates further south. SgurrEnergy with their global footprint are ideally placed to consult across the range although Scotland still makes up a significant portion of their renewable portfolio. Renewables by their nature can be intermittent in their operation. In general for renewable generation, export power varies as the wind speed or solar irradiation across the site fluctuates. This creates a variable loading pattern on the power transmission and distribution equipment connecting the site to the electrical grid. The loading pattern associated with the output from renewable energy fluctuates and cannot be controlled in the same way as more traditional embedded generation.

Electrical equipment is typically selected with appropriate static ratings to support the maximum export current (MVA) requirements (both steady state and transient fault current) however the maximum export capacity may only be realised for a fraction of the site operating profile.

2.1. Renewable energy systems

Solar Photovoltaic

Solar energy is variable over the year but more a consistent and predictable source than wind as you can predict for a lack of generation at night or reduced generation due to the low angle of incidence of the sun in winter. The energy available for a solar installation is defined by the global horizontal irradiation which is the total surface energy received on a unit area of receiving surface.

Thermal and voltage impacts on the DNO network are as per other embedded generation within these periods of generation.

Inverters in photovoltaic generation need to be maintained near to full load capacity to operate in their most efficient zone. Therefore it is common practice for inverters to be undersized by 20% of the installed peak capacity, thus operating in the high efficiency zone. This increases power delivery throughout the year, with only some losses in high summer due to the undersizing. It has been shown in studies that the conceptual design of a solar photovoltaic plant and the positioning of the inverters and combiner boxes can have a dramatic effect on copper losses (Papastergiou, 2010)

The electrical design of a photovoltaic generation site is split between DC and AC systems.

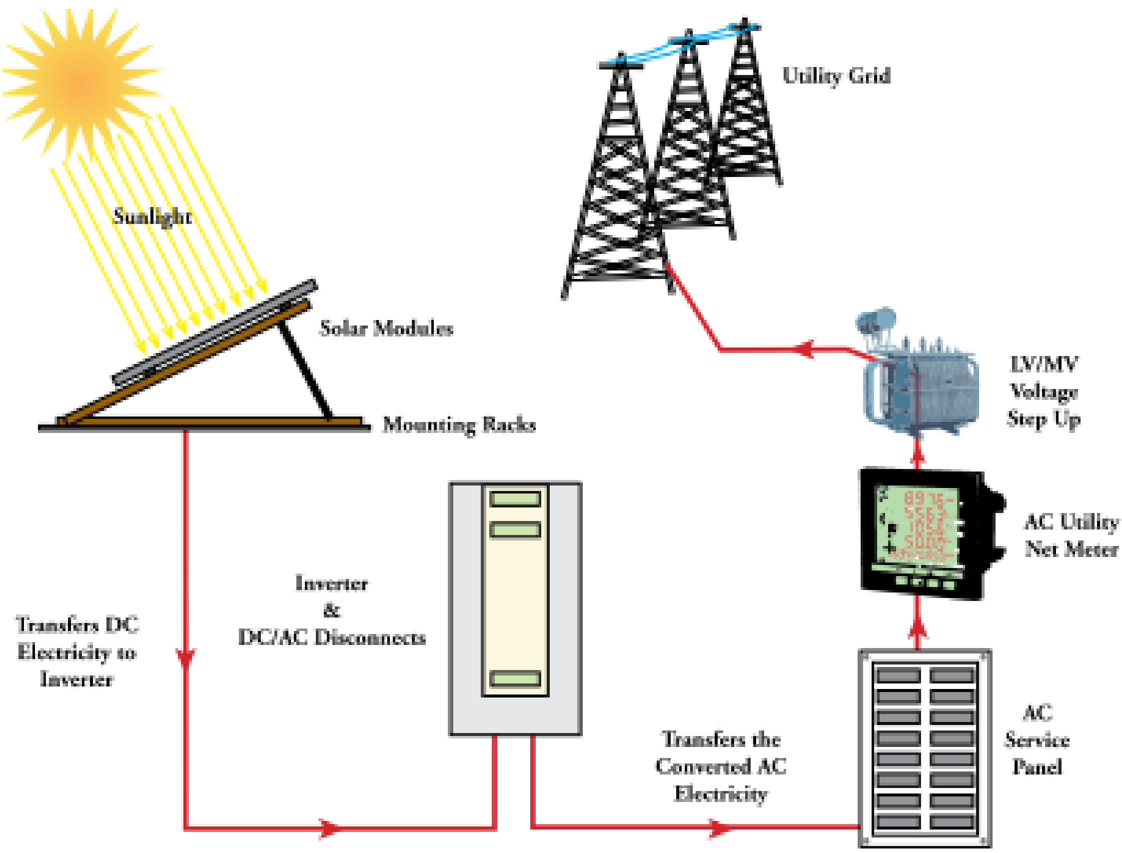

Figure 2-1Solar Photovoltaic layout (Alasdair Miller, 2010)

The DC system is made up of the following:

- Array(s) of PV modules.

- Inverters.
- DC cabling (module, string and main cable).
- DC connectors (plugs and sockets).
- Junction and combiner combiners.
- Disconnects and switches.
- Protection devices.
- Earthing.

The AC system is made up of the following:

- AC Cabling.
- Switchgear.
- Transformers.
- Substation.
- Earthing and surge protection.

Solar photovoltaic modules have non-linear output efficiency due to environmental effects such as shadowing and hot spots, electrical tolerances and different power output across cells, so MPPT is employed to smooth power delivery by using algorithms to sample power output and then alter the load across the string. These are normally included in the inverter hardware and so the output of the whole string is optimised based on the average.

There have been studies conducted in relation to PV plant design suggesting losses can be reduced by increasing the DC collector grid before step up to AC (Siddique, 2014), however it is the experience of the author that this technique is not in widespread use in the industry and is at an early stage of investigation.

Solar plants by their nature have a lower availability than wind generation so their output is measured by a solar plants performance ratio. This is normally shown as a percentage and is used to compare solar farm against each other. The performance ratio quantifies the overall losses on the rated output of a solar plant.

Onshore Wind

Onshore wind has been a significant influence in SgurrEnergy's entry into the renewable consultancy business. It is fitting as Scotland led the world in the development of electrical generation from wind, in fact the first wind powered electrical generator was built by Professor James Blyth in Scotland in 1887 (Price, 2005). With Scotland's windy climate it is natural that it should harness this abundant resource for its power generation needs. This is the case at the moment and Scotland has seen a rapid rise in recent years in the amount and scale of on shore wind farms being erected around the country and currently 60% of renewable energy is generated from wind farms both on shore and offshore. Whitelee windfarm in south west Scotland is the biggest onshore windfarm in Europe consisting of 140 turbines and generating a peak of 322MW of electricity (www.whiteleewindfarm.co.uk/about). With this rapid expansion has come criticism. Wind turbines, initially seen as elegant and futuristic have now become viewed eyesores in some quarters, ruining Scotland's scenic heritage in the eyes of many and pressure is now mounting to develop large scale offshore capability instead of onshore. However transmission and implementation costs for offshore generation rise considerably. Scotland does have extensive offshore pipeline and cabling experience due to the oil industry and it is hoped that this will drive costs down along with government renewable obligation certificates (ROC's). Unfortunately Scotland's early lead in wind turbine development wasn't protected at government level and that lead was lost to Denmark who now lead the world in technology implementation and development. This should be an incentive to not make the same national mistakes regarding offshore wind power development.

Onshore wind typically consists of a smaller number of turbines than offshore. Whitelee as discussed has over 100 turbines but typical installations are 10-20 turbines. Turbine outputs vary but maximum onshore turbine size is normally 3 MW due to local environment and planning issues.

Projects consist of ring or radial circuits of WTG's with their own transformers and switchgear stepping up the generation voltage to the site array voltage. This is then fed back via the site array to the site substation for connection to the distribution grid as shown in Figure 2-2

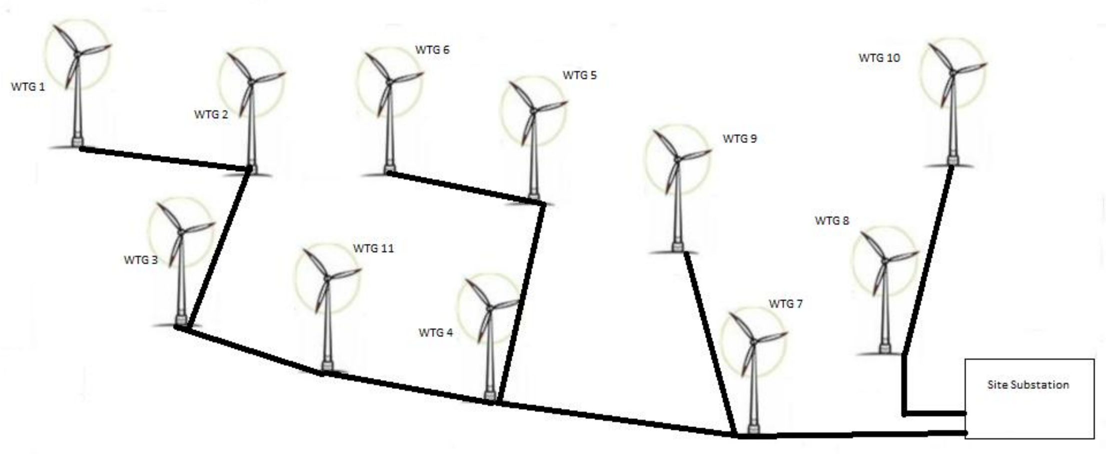

Figure 2-2 Typical site layout

These sites can take up a wide geographic area with cable runs into the tens of kilometres and so losses can be significant due to the large distances between the outlying WTG's and the export metering point.

Onshore wind farm electrical components consist of the following:

- WTG
- WTG Transformer
- Array cable
- Switchgear
- Export Transformer

Electrical losses will be recorded at all of these stages.

Offshore Wind

As the technology of wind generation has been optimised and up scaled, not to mention the permitting and social pressures being felt by the onshore wind industry, large scale offshore wind developments have witnessed a rapid rise to prominence and focus.

Offshore developments are becoming larger in scale. Not only are the number of turbines and arrays increasing in size, but the individual turbines are becoming larger with Vestas unveiling its 8 MW turbine prototype (www.renewable energyworld.com)

Figure 2-3 provides an overview of a typical UK offshore wind project and the boundaries of responsibility for the stakeholders involved in the construction and operation of a renewable energy connection to the electrical grid.

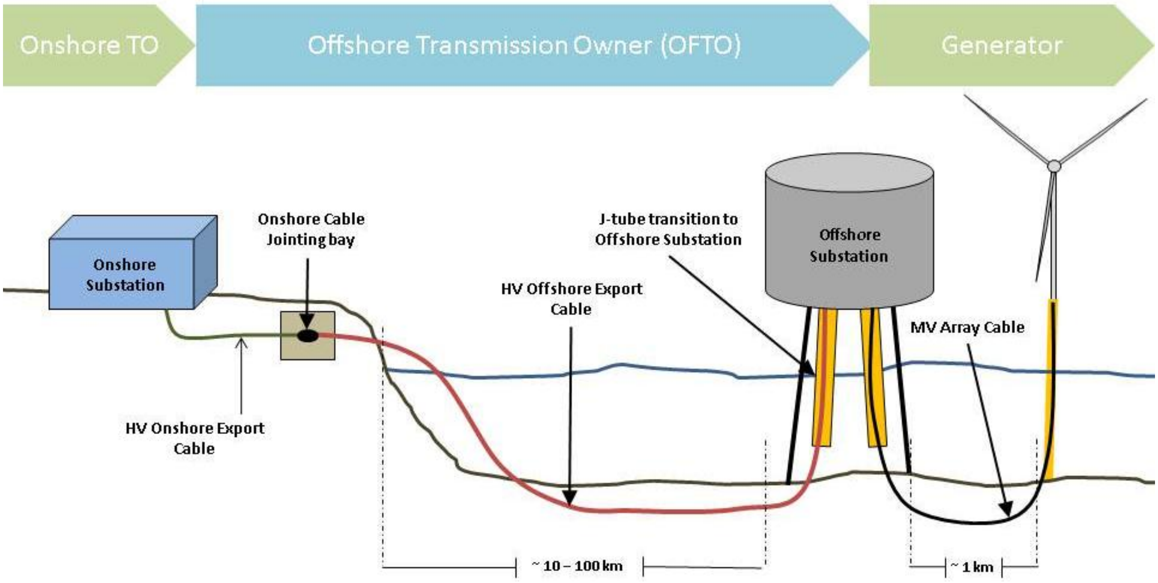

Figure 2-3: Offshore wind farm arrangement

With the larger distances involved in transmission from turbine to turbine and from the offshore substations, transmission losses through the cable may be increased. Offshore developments may mitigate for this by increasing the array voltages from 33 kV to 66 kV is some cases and by utilising HVDC technology at the offshore substation. The increase in costs for the capital expenditure can be significant for both the individual turbine 66 kV step up transformers and HVDC substations so any generation losses that can be saved by utilising these technologies must be able to offset these costs.

Electrical equipment in offshore environments is traditionally specified for continuous power ratings however it is known that electrical equipment such as cables and transformers may operate at higher ratings for periods of time. Under variable operating load conditions the temperature of the equipment is allowed to rise then cool as the load increases and decreases. In these situations it may be possible to apply a dynamic rating to equipment which may enable greater power export through electrical equipment.

Dynamic rating is a term that is applied to extending the rating of electrical equipment in operation for periods of minutes, hours or days depending on the requirement and constraints. It is essentially a decision to ‘overload’ electrical assets based on the knowledge that the equipment can withstand the overload period and magnitude.

Dynamic ratings have been applied by electrical network operators for many years and are based on the experience of the operator and their knowledge of the equipment. An operator may choose to knowingly allow the overload of a circuit in the network for an acceptable period to maintain availability. This is commonly known as “sweating” an electrical asset.

More recently dynamic ratings have been applied using information from temperature monitoring systems to enable the application of more accurate, continuous and measured ratings on electrical equipment, this is referred to as a real time thermal rating (RTTR).

The output of a RTTR system can theoretically be automatically integrated into the power control system however this is considered a potential future development once operators are comfortable with the feedback from a RTTR system philosophy.

In all cases overloading will increase the electrical losses to increased temperatures in the equipment but may be offset against potential losses due to curtailment of generation.

2.2. Electrical equipment

Cables

Figure 2-4 HV Power and control cables (Maximum HDMI Cable Length)

The transmission and distribution of the electrical power generated by renewable energy is carried to the grid connection point by electrical cables. These cables are located in trenches or buried underground, strung overhead on telegraph poles or pylons or laid in subsea trenches for offshore installations. Transmission and distribution voltages are usually carried on overhead lines in the UK with some undersea cables for interlink capability between Europe and Ireland. Array cabling is usually buried in trenches or direct in the soil using a cable plough.

Cables are manufactured using a low resistance conductor of copper or aluminium surrounded by an insulator to isolate the conductors from each other and their surroundings. Armouring and moisture resistant layers can also be incorporated increasing the complexity of the cable. These components all contribute to the losses of the cable.

There are four main types of insulation available for high voltage applications, XLPE (cross linked polyethylene), EPR (ethylene propylene rubber), MIND (Mass Impregnated Non Draining) and oil (Pressurised).

XLPE insulation has become the insulation of choice within the industry due to the low dielectric loss and high conductor operating temperature. XLPE insulation allows a continuous conductor operating temperature of 90ºC). XPLE cable due to reasons of market availability, potential impacts on the environment and ease of installation is the most common type cable encountered in renewable energy generation.

For the higher transmission voltages required for large scale offshore generation, higher capacity subsea cables are used. Insulation voltages of up to 150 kV are now becoming more common in three-core subsea XLPE cable applications. Transmission voltages up to 170 kV are not uncommon however and they represent the established end of the solid dielectric HV cable market. There is currently limited experience above this voltage level.

Submarine cables provide the means to collect and export power from the offshore WTGs to the wider grid onshore. In offshore wind farm installations there are two types of submarine cable:

- Inter Array Cables.
- Export Cables.

Inter array cables provide a collection system which connect the individual WTGs to the offshore substation while the export cables provide the connection from the offshore substation to the shore where there typically is a connection to a land based cable. Both types of cable are usually 3 core type with copper conductors, XLPE insulation and integral optical fibres as shown in Figure 2-5.

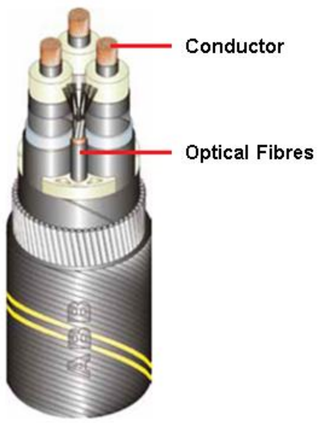

Figure 2-5: ABB offshore cable

Inter array cabling usually operates at 33 kV or 66 kV while export cables operate at voltages in excess of 100 kV.

Three-core submarine cables are available up to 245 kV using a solid dielectric (XLPE), and a number of wind farms under development have orders for cables rated for this voltage. This level of technology has limited service history and is still under development

There is a history of self-contained fluid filled insulated cables (a form of pressurised oil) being used for 400kV+ AC submarine cables but these are rare in the industry.

Losses in cables occur due to heat being dissipated when the cables are energised and under load. Cable losses can be split into Conductor losses, dielectric losses and sheath losses.

In solar photovoltaic applications low voltage DC is determined by national grid codes and regulations determined applicable to that country.
According the IFC solar guidebook, solar cable should meet the following criteria.

- The cable voltage rating. The voltage limits of the cable to which the PV string or array cable will be connected must be taken into account. Calculations of the maximum Voc voltage of the modules, adjusted for the site minimum design temperature, are used for this calculation.

- The current carrying capacity of the cable. The cable must be sized in accordance with the maximum current. It is important to remember to de-rate appropriately, taking into account the location of cable, the method of laying, number of cores and temperature. Care must be taken to size the cable for the worse case of reverse current in an array.

- The minimisation of cable losses. The cable voltage drop and the associated power losses must be as low possible. Normally, the voltage drop must be less than 3%, but national regulations must be consulted for guidance. Cable losses of less than 1% are achievable. (Alasdair Miller, 2010)

Cables for power generation are manufactured to recognised standards to ensure operational quality is met regardless of installation conditions. These standards include but are not limited to:

- BS 60228 Conductors of Insulated Cables

- IEC 60287 Electric Cables – Current Rating

- IEC 60840 Power Cables with extruded installation and their accessories

- IES 60853 Calculation of the cyclic rating and emergency current rating

A sample of commonly used cables, their common issue sizes and their parameters is given in Table 1 below.

Cable Size	**AC Resistance of Conductor at 90 deg C (μΩ / m)**	**AC Resistance of Conductor at 90 deg C (mΩ / m)**	**AC Resistance of Conductor at Theta m deg C (μΩ / m)**	**AC Resistance of Conductor at Theta m deg C (mΩ / km)**	**Current Carrying Capacity Direct Buried (A)**	**Dielectric Losses (kW / m)**
Al 35mm	1113	1.11	964.37	964.37	140	0.03
Al 50mm	822	0.82	712.23	712.23	173	0.03
Al 70mm	568	0.57	492.15	492.15	211	0.04
Al 95mm	410	0.41	355.25	355.25	252	0.04
Al 120mm	325	0.33	281.60	281.60	287	0.05
Al 150mm	265	0.27	229.61	229.61	320	0.05
Al 185mm	211	0.21	182.82	182.82	362	0.05
Al 240mm	161	0.16	139.50	139.50	421	0.06
Al 300mm	130	0.13	112.64	112.64	474	0.06
Al 400mm	102	0.10	88.38	88.38	538	0.07
Al 500mm	81	0.08	70.18	70.18	606	0.08
Al 630mm	64	0.06	55.45	55.45	686	0.09
Cu 50mm	448	0.45	388.17	388.17	232	0.09
Cu 70mm	320	0.32	277.27	277.27	278	0.11
Cu 95mm	237	0.24	204.92	204.92	328	0.12
Cu120mm	188	0.19	162.46	162.46	372	0.13
Cu150mm	150	0.15	130.32	130.32	418	0.13
Cu185mm	122	0.12	106.05	106.05	468	0.15
Cu240mm	95	0.10	82.31	82.31	537	0.16
Cu300mm	77	0.08	66.54	66.54	602	0.17
Cu400mm	59	0.06	51.03	51.03	691	0.19
Cu500mm	48	0.05	41.98	41.98	768	0.21
Cu630mm	40	0.04	34.83	34.83	850	0.23

Table 1 Common cable parameters (Moore, 1999)

Transformers

Transformers are required for all renewable energy systems to transform the power generated from the source at LV into MV for array collection and to transform the collected power for MV or HV export. The two main types of transformer used in renewable energy generation are:

- Laminated core.
- Oil filled.

WTG Transformers are provided to transform the LV output from the source into MV for collection in the array network. Transformers are typically rated to meet the source capacity and are located close to the generation source. In WTG's, transformers can be located in turbine, either in the nacelle, the base or outside, in offshore WTG's these can be located in the transition pieces of the offshore WTG structure. Solar PV transformers are located next to the inverters in bays throughout the solar farm.

Export transformers are required to transform the power from the array voltage to a higher export voltage for transmission to the grid. As these are required to export a significant amount of power from the whole generating plant they are usually much larger with larger potential for losses.

Transformer ratings and characteristics are given in the manufacturers transformer datasheet as shown in Figure 2-6

Electrical characteristics

Power (kVA)	50	100	160	250	315	400	500	630	800	1000	1250	1600	2000	2500
Primary voltage Secondary voltage	30kV 400 to 433V between phases, 231 to 250V phase to neutral (at no load)													
HV insulation level	36kV													
HV tapping range	± 2.5 % and/or ± 5 %													
Vector group	Yzn 5 / Yzn 11 (50kVA version only) - Dyn 5 / Dyn 11													
No-load losses (w) Load losses (w)	230 1450	380 2350	520 3350	780 4250	950 5150	1120 6200	1300 7200	1450 8800	1700 10500	2000 13000	2400 16000	2800 19200	3400 24000	4100 29400
Impedance voltage (%)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	6	6	6	6	6	6	6
Acoustic Level dB(A): - power L_{WA} - pressure L_{PA} (1m)	52 44	56 48	59 50	62 53	63 53	65 55	66 56	67 56	68 57	68 57	70 59	71 59	73 61	76 63

Figure 2-6 Schneider Electric Minera range Tx datasheet (http://www.schneider-electric.com/downloads)

Transformers associated with large scale renewable projects are typically oil insulated. Typically this provides a certain capability to operate in an overloaded condition for a period before thermal breakdown of the windings and insulation occurs. The heating and cooling of transformers is generally slower than with cables, therefore any rating 'bottle neck' is more associated with cables.

Power transformers are typically sized to carry the maximum continuous MVA rating of the project. Particularly for oil immersed transformers that are mostly used in renewable energy projects, it is common to allow a period of overload, sometimes up to 150% of continuous rating (depending on cooling system and insulation class).

This can often justify the under-sizing of transformers to save on size and cost which are both important factors in offshore projects where space and cost savings are of significant benefit.

Under-sizing of export or WTG transformers for rated output is not typical practice for wind projects. Export transformers are known to be sized to utilise short term overload capability in the event of outages. Therefore there is usually significant short term overload capability in these components.

The life expectancy of transformers, regulators and reactors at various operating temperatures is not accurately known. A typical transformer is guaranteed for the full lifetime of the project, which can range from 20 to 30 years.

IEC 60076-7 (Loading guide for oil-immersed power transformers) may be used to give an indication of permissible daily loading duties. This IEC standard can also be applied to transformer design when considering the variable nature of renewable energy generation.

Inverters

Inverters are used in renewable energy generation mainly in photovoltaic applications. The inverters are used to convert DC into AC for stepping up to grid distribution and transmission voltages.

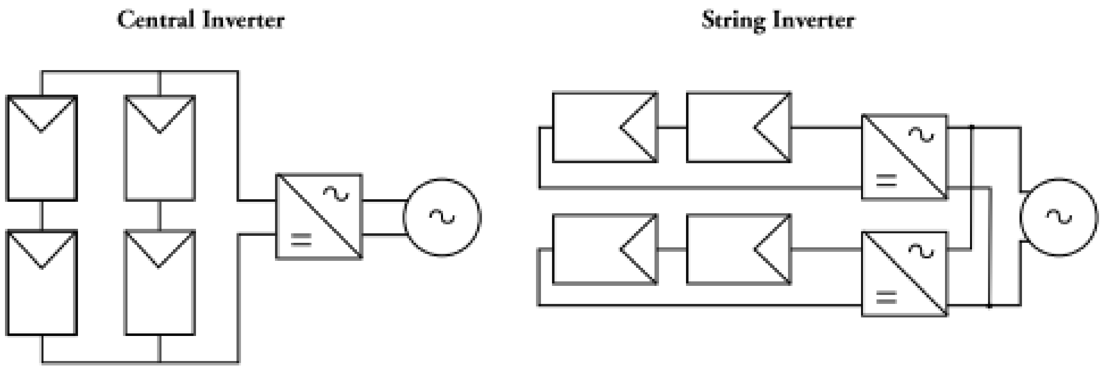

Figure 2-7 Inverter configurations (Alasdair Miller, 2010)

In photovoltaic applications, inverters may be string type or central type. Central inverters are used in medium to large photovoltaic installations typically over 5 MW. String inverters are typically used in photovoltaic installations under 10 MW but as pricing becomes more competitive they are becoming more prevalent.

Central inverters collate inputs from many strings and as such can suffer from losses due to an absence of maximum power point tracking and an increase in mismatch losses due to variance in array currents and voltages. Central inverters may also have inbuilt transformers which will contribute to the overall losses as documented in the transformer section.

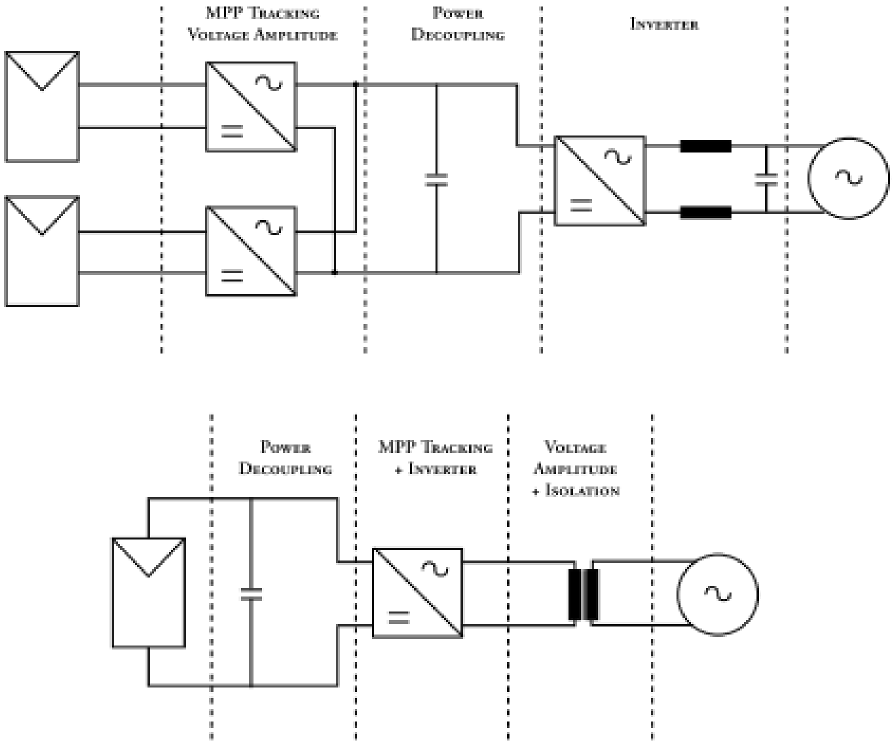

Figure 2-8 Transformer and transformerless inverter configuration (Alasdair Miller, 2010)

Sizing of a photovoltaic inverter will depend on the individual site parameters however most inverters will have a power ration between 0.8 and 1.2 given by:

$$Power\ Ratio = \frac{P(Inverter\ DC\ rated)}{P\ (PV\ Peak)}$$

Where

$$P\ (Inverter\ DC\ rated) = \frac{P(Inverter\ AC\ rated)}{n(100\%)}$$

The losses incurred by the each inverter type will be discussed in the next chapter.

3. Review of losses

3.1. <u>Electrical Losses</u>

Electrical losses occur due to many factors in renewable energy generation depending on the technology being utilised.

Ancillary System or parasitic losses are due to parasitic consumption within the generating facility. This may include losses for heaters or cooling systems, transformer no-load losses, safety equipment and control systems.

Grid compliance control losses can be due to limitations on the grid external to the renewable generator, both due to limitations on the amount of power delivered at a given time, as well as limitations on the rate of change of power deliveries. These could also include losses due to the power purchaser electing to not take power generated by the wind due to curtailment conditions detailed in the grid connection agreements between the generator and the DNO.

The electrical transmission efficiency including WTG transformers, solar inverters, collection wiring, substation transformers and transmission wiring will be reviewed as part of this study.

Cable Losses

Losses in electrical cables, whether they are onshore, offshore, buried or overhead line occur when the load on the cable generates heat in the various constituent parts. These consist of the conductor cores, the dielectric, any outer metallic layers or shielding and any external insulation.

The conductor losses are ohmic losses given by:

$$nI^2R_\theta \text{ (watt)}$$

Where n = number of cable cores

I = Current carried by the conductor (Amps)

R_θ= ohmic a.c. resistance of the conductor at θ^oC (Ω)

During the transmission of high A.C., the skin effect and proximity effect ensure that the current is not evenly distributed throughout the cross section of the conductor. The skin effect occurs when the cable is constructed from a large number of concentric circular elements such as a stranded cable shown in Figure 3-1 .

Figure 3-1 Stranded cable (Moore, 1999)

The strands at the centre of the cable are surrounded by more strands and as such are subjected to a greater magnetic flux than those strands on the outside of the cable. This causes the current density to be greater on the outside of the cable than it is at the centre. The increase in current density results in an increase in conductor resistance which in turn will contribute to the overall losses.

The proximity effect also contributes to overall cable losses. In this instance overlapping magnetic fields between closely arranged conductors interact via their respective magnetic fields.

In both cases these losses and effects can be reduced by innovative cable design and conductor arrangement and shaping. One such design is the milliken conductor which uses shaped groups of conductors to reduce the effects.

Figure 3-2 Miliken Conductor cross section (associates)

Dielectric losses

These losses whether they are conductor, dielectric or sheath all contribute to the overall losses and have to dissipate into the surrounding medium whatever that may be. This may be directly in the ground, a cable duct, the open air or water.
It should be noted that in DC operation at higher voltages in the transmission range, the DC leakage has such a small magnitude that is can be viewed as insignificant to any overall loss calculations (Moore, 1999). This would be a consideration in HVDC applications for large scale offshore wind generation.

In all cases cable manufactures such as Prysmian, Nexans and ABB provide datasheets with rating data for their range of applications. This information can be used to populate the loss tool cable datasets.

Transformer Losses

Transformers are a key component of renewable generation as they step up the voltage at the point of generation from low voltage, typically 400-600V, to medium to high voltages of 20 kV and above. Typically in the UK, step up voltages are 33 kV for distribution connection and 132 kV for transmission kV although higher EHV connections are coming into practice for larger offshore wind developments such as

London array which has two offshore substations exporting via two Nexans 150 kV XLPE submarine export cables (www.nexans.com/news)

As previously discussed the higher the export voltage, the less the transmission, export and distribution losses will be over the length of the cable. Depending on the circuit configuration, the metering point of the generation plant is likely to be on the export side of the metering switchgear after the step up transformer. This means that any losses before this point will be part of the site electrical losses.

Transformers are subject to losses in both the core and the windings. The current required for magnetising the core in order for it to cycle the magnetic flux at the system frequency dissipates energy. This is commonly known as the no load loss. This occurs whenever the transformer is energised.

Load losses also occur whenever there is a flow of current in the system. This is determined by the magnitude of the current and the resistance of the system. This is especially marked in the transformer windings. These losses only occur when the transformer is under load. (Heathcote, 2008)

These losses are given as part of the manufacturers' datasheets and along with the efficiency and transformer ratings can be input into the loss tool datasets as tool is expanded. It should be noted that forced cooling by either oil or air flow can reduce the temperature of the windings. This allows the transformer to either operate at a higher rating or the temperature losses can be reduced.

Inverter Losses

Inverter losses in Solar PV are a smaller contributer to the overall loss calculation than either the cables or transformers. As most inverters are transformerless, the losses are concentrated on the semiconductor components of the inverter circuitry. These losses are ususlly in the order of 95% with peak efficiency od up to 98% in transformerless inverters (Luo, 2013). Inverter efficiency is measured according to IEC 61683 to ensure compliance.

Datasheets provided publicly for inverters commonly used in solar PV generation projects provide the efficiencies and ratings that may be used for calculations. The datasheet and values for the Freesun HED-UL Central inverter are shown in Figure 3-3.

		390VAC					360VAC	330VAC	208VAC
		FRAME 2		FRAME 3			FRAME 3	FRAME 3	FRAME 3
NUMBER OF MODULES		5	6	7	8	8	8	8	8
MODEL NUMBER		FS0751CU-PU	FS0900CU-PU	FS1050CU-PU	FS1200CU-PU	FS1250CU-PU	FS1110CU-PU	FS1001CU-PU	FS0640CU-PU
OUTPUT	Continuous AC Output Power (kVA)[1]	750	900	1050	1200	1250	1110	1000	640
	Max. apparent Power (kVA)[2]	825	990	1155	1320	1350	1220	1100	704
	Continuous Output AC Current(A)	1110	1332	1554	1776	1852	1778	1750	1776
	Power Factor (cos phi)/@max. power	0.0 leading...0.0 lagging / 0.90 leading ... 0.90 lagging (adjustable)							
INPUT	MPPt range (VDC)[3]	585V-820V					540V-820V	500V-820V	330V-600V
	Max. permissible DC voltage	1000V					1000V	1000V	600V
	Max. continuous DC current (A)	1250A	1500A	1750A	2000A	2000A	2000A	2000A	2000A
	Max. short circuit DC current (A)	1625A	1950A	2275A	2600A	2600A	2600A	2600A	2600A
EFFICIENCY & AUX. SUPPLY	Max. Efficiency PAC, nom (η)	98.6%							
	Weighted CEC Efficiency (η)	98.0%							
	Max. Standby Consumption (Pnight)	< approx. 40W/per module							
	Control Power Supply	10 kVA Built-in Internal transformer as standard (Optional external 3x208VAC power supply)							
	Avg. Power Consumption	2300W	2760W	3220W	3680W	3680W	3680W	3680W	3680W
CABINET	Dimensions [WxDxH] mm – mm[4]	3900x1020x2400		4900x1020x2400					
	Dimensions [WxDxH] mm – inches[4]	153.5 x 40.2 x 94.5		192.9 x 40.2 x 94.5					
	Weight[5] – kg	3850		4900					
	Weight[5] – lbs	8500		10800					
ENVIRON-MENT	Degree of protection	NEMA 3R							
	Permissible Ambient Temperature[6]	-4°F to +122° F / -20°C ...+50°C							
	Relative Humidity	4% to 100%							
	Max. Altitude (above sea level)[6]	1000m; >1000m power derating 1% Sn (kVA) per 100m							
CONTROL INTERFACE	Interface	Alphanumeric display, ON-OFF Selector, E-Stop (Optional)							
	Communication	RS232 / RS485 / USB / Ethernet, (Modbus RTU Protocol, Modbus TCP/IP)							
	Analogue Inputs	1 programmable and differential inputs; (0-20mA or ± 10mV to ± 10V) and PT100							
	Digital Outputs	2 electrically-isolated programmable switched relays (250VAC, 8A or 30 VDC, 8A)							
PROTECTIONS	Ground Fault Protection	Grounded PV array (Positive pole and negative pole): GFDI protection per MPP Floating PV array: Isolation Monitoring per MPP							
	PV Array protection DU box (HEC-UL+)	Max. 4x700A switches. Max. 32 inputs (70-200A fuse). Max. 28 (400A fuse) Max. 3x1250A switches. Max. 24 inputs (70-200A fuse). Max. 21 inputs (400A fuse)							
	PV Zone monitoring	Up 24 Independent CT's							
	Overvoltage Protection	DC and AC Inverter sides (Type 4) and Auxiliary Supply type 2- Internal Standard							
	Lightning Protections	Optional (Integrated in the inverter)							

NOTES [1] Values at 50°C.
[2] Maximum ambient temperature 40°C.
[3] Values at 1.00·Vac nom and cos ø= 1.
[4] Units with integrated DU subsystem (HEC+) will increase 1000mm (39.4") in width.
[5] Preliminary. Consult Power Electronics.
[6] Other characteristics consult with Power Electronics.

Figure 3-3Freesun HEC-UL Inverter characteristics (Electronics, 2013)

This information is freely available for majority of inverters encountered in solar PV projects. Therefore a database of inverter ratings and efficiencies can be constructed for input into the loss calculation tool.

Typical efficiencies for low medium and high efficiency inverters are shown in *Figure 3-4*

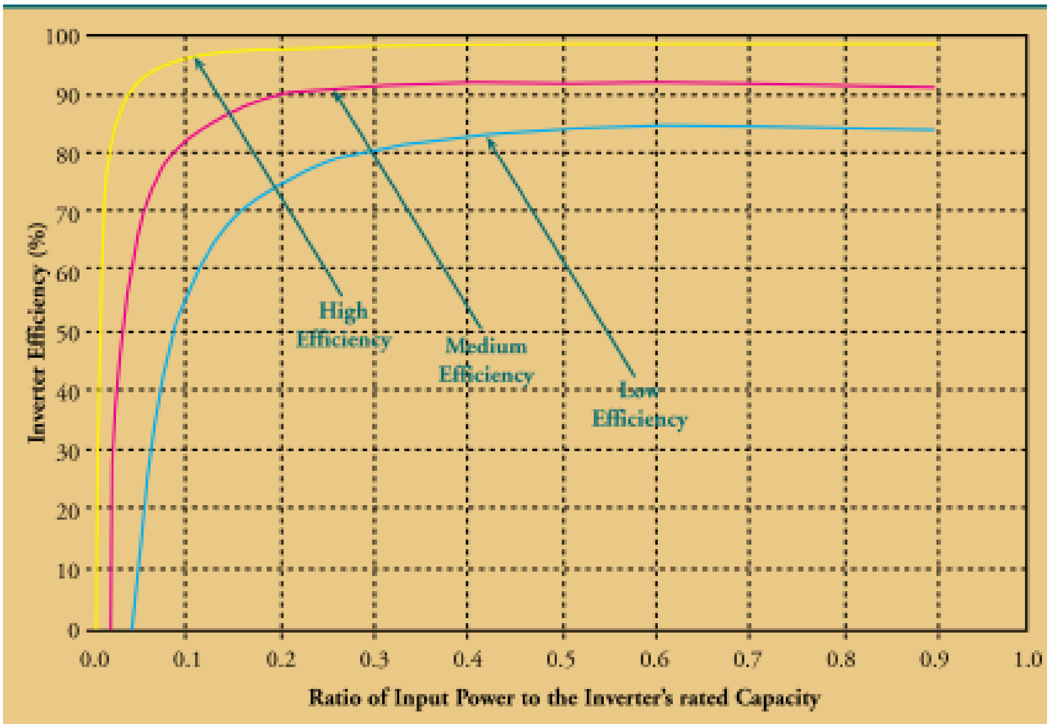

Figure 3-4 Inverter efficiencies (Alasdair Miller, 2010)

Inverters are manufactured to ensure their efficiencies are in accordance with IEC 61683:1999 Photovoltaic systems – Power conditioners –Procedure for measuring efficiency.

3.2. Data acquisition

Loss data has been acquired from SgurrEnergy's large and varied portfolio. As discussed, SgurrEnergy's profile is wide and varied, however on and off shore wind along with Solar PV make up the bulk of their business interests. To this end it was decided to take three of the most used technologies along with three examples of each of these to ensure a wide sample of loss data could be tested against the model.

An example of an on shore wind farm operational report data is shown below in Table 2

Months	Energy Exported[1] (GWh)	Energy Generated (GWh)	Budget Energy (GWh)	Export Variance[2] (%)	Overall Operational Availability (%)	Budgeted Overall Operational Availability (%)	Availability Variance (% points)
Oct-11	2.82	2.83	2.36	19.0%	95.5%	96.8%	-1.3%
Nov-11	1.97	1.98	2.52	-21.6%	92.3%	96.8%	-4.5%

Dec-11	3.92	3.94	2.52	55.7%	99.9%	96.8%	3.1%
Jan-12	3.02	3.04	2.89	4.6%	98.3%	96.8%	1.5%
Feb-12	1.82	1.83	2.29	-20.4%	100.0%	96.8%	3.2%
Mar-12	1.44	1.45	2.35	-38.6%	98.5%	96.8%	1.7%
2011-2012 Financial Year Total	**14.99**	**15.07**	**14.93**	**0.4%**	**97.4%**	**96.8%**	**0.6%**
Apr-12	2.01	2.02	1.79	12.5%	98.90%	96.80%	2.1%
May-12	1.76	1.77	1.99	-11.6%	99.90%	96.80%	3.1%
Jun-12	2.36	2.37	1.39	69.8%	100.00%	96.80%	3.2%
Jul-12	1.31	1.31	1.64	-20.4%	99.50%	96.80%	2.7%
Aug-12	1.63	1.64	1.65	-1.2%	99.70%	96.80%	2.9%

Table 2 Windfarm 1 operational report data

Technical data from the equipment manufacturers was also acquired from datasheets and reference books.

A selection of cable data is shown below in Table 3 . The site location and manufacturer name has been omitted for non-disclosure reasons.

OHL	**OHL Conductor Size**	**AC Resistance of Conductor at 75 deg C (mΩ / m)**	**AC Resistance of Conductor at 75 deg C (µΩ / m)**	**AC Resistance of Conductor at Theta m deg C (µΩ / m)**	**DC Resistance of Conductor @ 20 deg C (Ω / km)**	**Current Rating (Temperate Climate) (A)**
HD Cu 16mm	16					
HD Cu 32mm	32					
AAAC Almond 25mm	25	1.321	1320.90		1.11	162
AAAC Fir 40mm	40	0.833	833.00		0.7	217
AAAC Hazel 50mm	50	0.665	665.21		0.559	250
AAAC Willow 75mm	75	0.444	443.87		0.373	322
AAAC Oak 100mm	100	0.336	335.58		0.282	384
AAAC Ash 150mm	150	0.220	220.15		0.185	501
AAAC Upas 300mm	300	0.110	110.08		0.0925	776
ACSR Gopher 25mm	25	1.338	1337.50		1.07	160
ACSR Rabbit 50mm	50	0.661	661.25		0.529	243
ACSR Dog 100mm	100	0.335	335.00		0.268	390

ACSR Wolf 150mm	150	0.223	222.50		0.178	512
ACSR Lynx 175mm	175	0.191	191.25		0.153	562
ACSR Panther 200mm	200	0.165	165.00		0.132	615
ACSR Zebra 400mm	400	0.083	82.75		0.0662	931

Table 3 Cable data acquisition

A selection of the transformer data is shown below in Table 4. The site location and manufacturer name has been omitted for non-disclosure reasons.

Power (MVA)		**Losses (kW)**			**Voltage (kV)**
ONAN	**ONAF**	**NLL**	**LL**	**Total losses**	
8	10	8.5	63	71.5	
12	15	10.5	74	84.5	38/20
12	15				38/20
16	20	12.5	85	97.5	38/20
24	30				38/20
31.5	40	22	177.37	199.37	
48	60				110/20
	60	24.5	240	264.5	110/20
60	75	29	259	288	110/20
	75	27.5	280	307.5	110/20
70	88	42	345	387	
80	100	38	423	461	110/20
80	100				110/20
80	100	47	190	237	110/20
	100	33.5	335	368.5	110/20
84	**112**				**138/34.5/313.8**
90	120	38	423	461	110/20/10

Table 4 Transformer data acquisition

4. Loss Tool

4.1. Software specification and design

The tool has to be able to be used in an office environment primarily in the electrical department at SgurrEnergy, but across departments and in the global offices if required. This narrows down the software options somewhat. The author decided that using a software package that required a paid licence would not be cost effective and transference of data across departments would be problematic. Dedicated non licenced software packages would remove the cost issue but there would be a training aspect involved.

It was decided to use Microsoft Excel as the basis for the loss calculation tool as this is readily available as part of the Microsoft office package installed on all the SgurrEnergy computer systems across all the business departments and regions.

Microsoft Excel has the capability of storing multiple data sets. This is a requisite as large amounts of cable, transformer and inverter data will be stored as a reference within the tool.

This data will need to be pulled depending on the project technical parameters. Excel allows this with the VLOOKUP function and tis inbuilt logic functions.

The tool has to be able to differentiate between different technologies and only pull data that is relevant to that chosen technology.

This is performed with drop down menus on the front page. These are selectable with the generation technology required. The parameters required for the chosen technology then become available, all others being ignored.

Once all the required parameters and known inputs have been selected, the tool will look up the datasets for the technical values and perform the calculation and show the loss value as both a value and percentage of the total as required.

4.2. Development of tool

Input Parameters

The tool has been designed from the outset to be user friendly from the outset. This requires input parameters to be relevant and easily identified.

Firstly the type of renewable generation technology is to be defined by the user. Each technology will have different parameters linked to it for referencing. The technologies included in this version of the tool are as follows:

- Solar Photovoltaic
- Onshore Wind
- Offshore Wind

These three technologies represent 80% of SgurrEnergy's current workload and as such are relevant to the vast number of investor and due diligence queries regarding electrical losses. The flexibility of the tool will ensure that more technologies can be included as well as more datasets for the existing ones as new technology is developed.

Each technology will have different input parameters that are exclusive to that type of technology and will have stored datasets for the tool to access. A choice of one particular technology will lock out parameters and datasets not relating to that technology. This will keep the inputs and therefore calculations and outputs accurate.

Once the user has chosen the technology, the next stage will be to choose the number of generating units. Depending on the application, these may be WTG's or solar inverters.

The inputs required for all technologies are as follows:

- Technology Type
- Number of generating units
- Generating Unit rating (MW)
- Maximum power factor setting

The Total rating is calculated by multiplying the unit rating by the number of units.

The Maximum MVA is given by dividing the total rating by the maximum power factor.

An example of the layout of the plant definition input section is shown in Table 5

PLANT GENERAL DEFINITION - For Solar, Inverters are	**Unit rating (MW)**	2
	Number of generating units	11
	Total Rating (MW)	22
	Maximum Power Factor Setting	0.95

considered generating units	**Maximum MVA**	23
	Technology	Offshore Wind

Table 5 Plant definition input

As demonstrated above, the yellow boxes require a user input while the white boxes give a calculated value to be factored into the overall loss calculation.

Inputs

Depending on the renewable energy technology that has been selected, the user has to input circuit items that are relevant to the site.

To enable the parameters and calculations to be managed appropriately for a solar photovoltaic generation plant, solar inverters are classed as the generating units in this instance. The rating of the inverter will be taken from the manufacturer's datasheet and input by the user.

With this determined, the next operation is for the user to input the required parameters for solar photovoltaic generation. These are the following:

- Site Voltage (kV)
- Array cable type (Cross sectional area (mm^2))
- Array cable length
- Number of transformers
- Transformer size (MVA)

It should be noted that in renewable energy installations, multiple cable types may be used throughout the installation. This is especially true if the central inverter concept is used in solar photovoltaic generation, as used as more strings may be combined into the same circuit before step up. The same consideration will apply to radial circuits for wind generation. The tool therefore has facility to input nine different cable types. The flexibility of the tool allows this to be expanded if required in the future.

Once the cable type is selected, the tool will pull the cable parameters from the stored data sets. These parameters are taken from sources such as manufacturer's cable data sheets such as Prysmian, Nexans or the BICC Electric Cable Handbook (Moore, 1999).

These cable parameters include the following:

- Conductor CSA (mm^2)
- Insulation CSA (mm^2)
- Conductor resistance DC 20^{o}C (Ω/km)
- Conductor resistance AC 90^{o}C (Ω/km)
- Insulation resistance 20^{o}C (Ω/km)
- Capacitance (µF/mm)
- Inductance (mH/km)
- Current Rating (A)
- MVA rating @ V (MVA)
- Losses (W/m)

MVA rating for each cable is given by the following:

$$\frac{\sqrt[3]{(AV)}}{1000000}$$

Where A is the current rating and V is the array voltage.

Array Cable losses are then calculated by taking the stated cable losses for that type of cable and multiplying by the length of cable.

Each array cable type losses are then added as shown in Table 6.

Only two standard cable types are input in this example with a CSA of 95 mm^2 and 240 mm^2 and the losses are demonstrated for the input lengths.

ARRAY CABLES DEFINITI ON	**Array Cables Voltage (kV)**	33			
	Array Cables	**Size (mm^2)**	**Total length (m)**	**Losses (W/m)**	**Total Losses (W)**
	Cable Type 1	240	547	72	39384
	Cable Type 2	95	5377	63	338751
	Cable Type 3			0	0
	Cable Type 4			0	0
	Cable Type 5			0	0
	Cable Type 6			0	0
	Cable Type 7			0	0
	Cable Type 8			0	0
	Cable Type 9			0	0

Table 6 Array cable input

Once the array cable losses are calculated the transformer losses are then determined. Depending on the site configuration and layout design parameters, there may be several stages of step up transformation performed. Typically in wind sites, WTG's have a transformer stage as well as the site having a transmission or distribution transformer stage. Therefore there are input slots in place to be used by the operator as required. In this way all transformer losses may be taken into account for the final calculation.

These losses are determined by inputting first the number of transformers and their MVA rating. The load losses (W) are then input by the user from the manufacturer's data sheets dependant on which make of transformer is being used.

The total losses can then be calculated by multiplying the individual load losses by the number of transformers.

	Transformers	Num ber	Size (MVA)	Load Losses (W)	Total Losses (W)
TRANSFORMERS DEFINITION	Transformer Type 1 (e.g. WTG)	11	2.1	16600	182600
	Transformer Type 2 (e.g. Export Tx)	0	0	0	0
	Transformer Type 3	0	0	0	0

Table 7 Transformer Input

The final loss calculation is performed on the export cable if required. The inputs are shown in Table 8. There are a number of options as shown. The ability to choose AC or Dc cable is available however the tool has not been equipped with the ability to calculate these at this time and would be a development of the tool in time as this becomes a more prevalent technology. The tool was designed to allow relatively easy development if required.

EXPORT CABLE DEFINITION	Export Cable	AC
	Number of Export Circuits	2
	Export Cable Voltage (kV)	245
	Total Export Current (A)	55
	Current Per Circuit (A)	27
	Export Cable length (m)	70000
	Export Cable size (mm^2)	630
	DC Resistance of Export Cable Cores (per core) (ohms)	0.027
	AC Resistance of Export Cable Cores (per core) (ohms)	0.036
	AC Resistance of each circuit over export cable length (ohms)	7.565
	Full load Losses on Export Cables (MW)	0.011

Table 8 Array cable input

Assumptions and exclusions

Typical cable data including current ratings and cable mass was taken from publically available data published by BICC Cables (Moore, 1999). Specific values of cable losses per km and costs for different cable sizes could not be provided by any cable manufacturer as the information was described as commercially sensitive and project specific.

Resistance of the export cables has been assumed as equal to the DC conductor resistance (neglecting temperature rise) based on IEC 60287:

$$R' = \rho \frac{l}{A}$$

R' = DC conductor resistance

ρ = resistivity of conductor (1.7×10^{-8} for Copper)

l = Length of conductor

A = Cross-Section Area of conductor

The above values of resistance are based on a temperature of 20˚C. Resistivity of the conductor will vary with temperature, with the resistance increasing as temperature increases. This variation can be simplified to a linear function for a reasonable temperature range as follows (neglected from this assessment):

$$R = R_{20}\,[1+\alpha(T-20)]$$

R = the resistance of the conductor at temperature T

R_{20} = conductor resistance at 20˚C

T = operating temperature of the conductor (90˚C)

α = temperature coefficient of resistivity

Actual values of α, depend on the composition of the material in addition to the temperature. For both copper and aluminium, a value of 0.0039 for α will give sufficient accuracy for most conductor calculations.

NB. For a complete resistive losses analysis, the complex thermal model of the export cables should be considered.

- The density of copper has been taken as 8690 kg/m^3.

The spreadsheet model was used to calculate indicative figures for:

- Losses in the export cables.
- Losses in the array cables.
- Losses in the transformers.
- Estimation of losses cost for various cable sizes and distances.

It should be noted that these losses are calculated on the basis of the generation plant being at full load. This will satisfy the investors' requirement for worst case scenario prediction ability.

4.3. Verification

To verify that the calculations and VLOOKUP programs collate the correct data and manipulate it in the correct way for each technology, a series of tests were conducted.

Model testing

The model was tested in a methodological way. The tool requires information from various sources to be input.
These are as follows:

- Technology Type
    - Onshore Wind
        - Number of Units
        - Rating
    - Off shore Wind
        - Number of Units
        - Rating
    - Solar Photovoltaic
        - Number of Inverters

        - Rating
- Cable Type
    - Array
        - CSA
        - Length
    - Export
        - CSA
        - Length
- Export Transformer
    - Number
    - Rating

All of these inputs have a corresponding lookup table in a separate tab as shown in Figure 4-1. The VLOOKUP function allows excel to pull data from any tab and fill it in automatically depending on the user input.

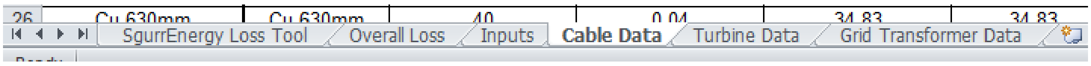

Figure 4-1 Tab definition

Each technology was selected in turn to ensure that only the relevant datasheets were available to input.

Then each parameter was checked in turn and the value cross referenced.

Cable type was checked, if copper was selected was the copper dataset accessed. If Aluminium was selected, was the aluminium dataset selected. In both of these instances there were no issues and the correct datasets were accessed.

The cable parameters were then checked. A value of CSA was input between 30 mm^2 and 630 mm^2 along with a standard unit length of 1000 metres. The value given for the losses was checked against the BICC Electric Cables handbook data tables for authenticity. This test was performed for both copper and aluminium cable. There were a few numerical errors within the dataset (duplication and some magnitude errors) but these were debugged out through a process of elimination.

The process was continued with the export cable parameters, the generator (turbine/inverter) units and the grid transformers. Again there were some numerical errors and one calculation error but these were debugged until operation was correct.

The tool was then given to a colleague, David Partington who is the Principle Electrical Engineer in SgurrEnergy for verification. The final checks were performed and Mr Partington input some models of his own to check the validity of the calculations. These checked out and the user was confident that the tool could perform the task required.

With the mechanics of the tool and user confidence in the calculations bringing a loss calculation to within the required magnitude and within the expected range and therefore achieving proof of concept, a case study was the next step to prove that the tool was fit for purpose.

5. Case study

SgurrEnergy within its extensive global portfolio of projects has access to generation data across a wide variety of generation technologies. These also vary in scale from kilowatt single turbines to multi megawatt offshore installations. A case study was carried out using loss data from a typical operational onshore wind farm in the UK. This is typical of the type of project that investors and due diligence financial investigation require loss calculations for. This would allow the loss calculations from the tool to be compared to actual yield data from the site.

The name of the windfarm can't be disclosed due to operational reasons but the data may be used for analysis.

5.1. Technical review

The wind farm consists of 11 Vestas V80 2.0 MW wind turbine generators (WTGs) a, giving a total rated capacity of 22 MW for the Project as a whole. The WTGs are a three phase synchronous generator type with a permanent magnet rotor that is connected to the grid through a full converter. The output voltage of the converter is 650 V which is stepped up to 33 kV by a transformer located in the WTG nacelle. The medium voltage switchgear located at the tower base of the WTG allows the WTG to be electrically isolated as required without affecting the wider wind farm network. Due to local grid conditions indicated by the DNO, the wind farm is constrained to 18.4 MW.

The operational frequency of the wind farm is 50 Hz and the Power factor of the site is given as 0.95 lagging.

These WTGs have hub heights of 60 m (six WTGs) and 78 m (five WTGs), a rotor diameter of 80 m and maximum tip height of 118 m.

The WTGs are connected by a network of buried XLPE copper cables each with a conductor cross sectional area of 95 mm^2 or 250 mm^2 depending on position in the array. These cable sizes are suitable for the installation. The WTGs are connected via the MV cable network to the wind farm substation MV switchgear. The substation MV switchgear type is Safeplus manufactured by ABB. This switchgear is commonly used in wind farms and appears to be appropriate for this application. The Turbines are arranged in two strings from a central substation as shown in Figure 5-1

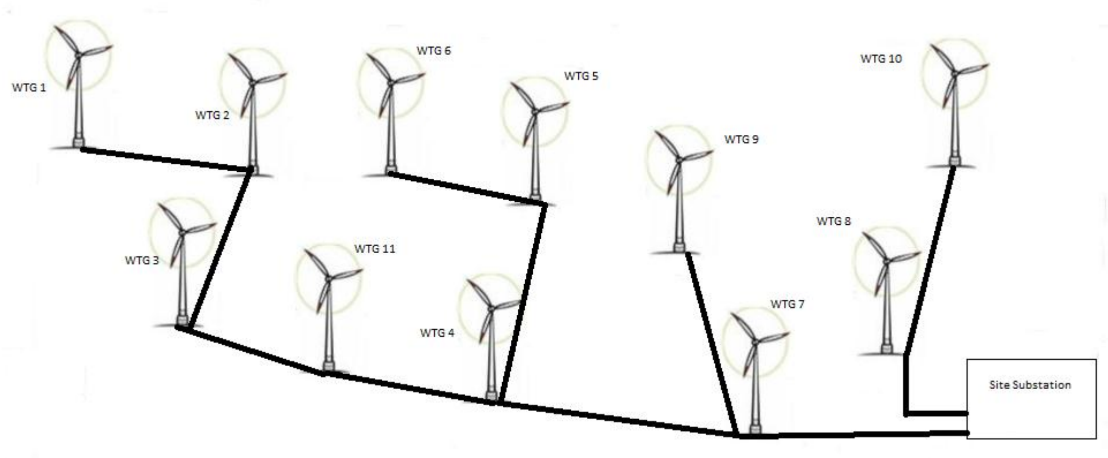

Figure 5-1 Case Study Windfarm layout

The cable arrangement for the site is shown in Table 9

Circuit Node	Circuit Node	Length (m)	Cable size (mm)
Substation	WTG 7	95	240
WTG 7	WTG 9	714	95
WTG 7	WTG 4	452	240
WTG 4	WTG 5	362	95
WTG 5	WTG 6	914	95
WTG 4	WTG 11	893	95
WTG 11	WTG 3	562	95
WTG 3	WTG 2	462	95
WTG 2	WTG 1	494	95
Substation	WTG 8	540	95
WTG 8	WTG 10	436	95

Table 9Case Study array cable arrangement

The total array cable distance is 5924

5377 metres of 95 mm^2 cable

547 metres of 240 mm^2 cable

A high level energy yield prediction based on operational production data has been undertaken to understand the expected output. The assessment consists of a review of production and availability of the entire wind farm over the operational period considered, and relates this to reference wind speed data. A revised energy yield prediction and uncertainty analysis is conducted using monthly energy production and reference wind speed data. This is delivered in the form of monthly operational reports as described in 3.2.

The measured output given in the operational data for the site during the period January 2012 to June 2012 is shown below in Table 10

MWh	Actual Generation	Budget Generation	Variance
January 12	6,839	6,962	(123
February 12	4,271	6,227	(1,956
March 12	4,720	6,619	(1,899
April 12	6,098	6,102	(4
May 12	6,026	5,976	50
June 12	3,247	5,663	(2,415
	31,201	37,548	(6,347

Table 10 Case study operational data

These figures show an approximate variance of 17% over the period. The reasons for this are due to the availability of the site including downtime as shown in *Table 11*

Availability

	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13
Technical Availability	94.9%	95.2%	98.7%	97.7%	98.2%	99.1%
Overall Availability	94.5%	94.7%	94.7%	94.4%	98.1%	99.0%

Table 11 Case Study availability

The technical availability of the site due to downtime was never 100% over the operational period. The total time unavailable over this period is given as 16.2 %. This is not unusual for a wind farm of this size and location. The maintenance reports confirm that there were a series of faults contributing to lack of generation.

February – 23 hours out of service due to high winds

March – 1207 hours out of service due to termination remedial works

April – 87 hours Turbine 8 Hydraulic fault

-67 hours Turbine 10 electrical fault

May – 4 day outage essential grid maintenance

June – Turbines 2,6,7 electrical faults

-75 hours grid curtailment

It can be derived that the generator has lost 17 % production over the period with 16 % of that due to availability issues. Approximately 0.5% of that is related to electrical faults across the turbines. It may then be approximated that the expected electrical losses for the plant over the period should be in the region of around 1.5 % of the total.

It should be noted that some assumptions have been made due to the lack of actual metered data and specific electrical losses per fault.

The site parameters were fed into the loss tool and the results witnessed in 5.2.

5.2. Results

Once all the parameters of the site were entered into the loss prediction tool the following losses as shown in **Error! Reference source not found.**

Description	Remarks	Total Losses (Watts)	Percentage of Max Output
MV Collector Cables	At estimated Operating Temperature	65,067	0.352%
2100KVA Export Transformer	Standard Losses	226,416	1.224%
LV Cables	Ignore Losses	0	0.000%
Total		***292,606***	***1.582%***

Table 12 Case study loss calculation results

The loss calculation tool calculates the electrical losses to be 1.582 % which according to the operational reports would be the expected losses from the electrical components.

6. Conclusions

The main conclusion is that the tool performs to the level required by the electrical department at SgurrEnergy. The calculations are within the correct order of magnitude and the figures from the case study show that the tool calculates the losses to a reasonable accuracy.

Some assumptions were made due to the lack of metered data but should not affect the overall accuracy too much.

The tool should become more accurate with more datasets including inverters, WTG transformers and transformers.

Metered data from the site would have conclusively proven the tools accuracy and it is hoped that SgurrEnergy's new O&M department will be able to supply this for future projects.

The tool is not capable at the moment of replicating HV DC cable transmission losses and as this is expected to be a growing market this omission should be rectified over time.

The purpose of this thesis was to produce a tool that would provide accurate electrical loss calculations for investors to be confidence with. The author concludes that this has been achieved.

7. Further Work

If more time was available or further academic study was pursued, the following topics could have been explored in relation to this body of work:

- High Voltage Direct Current (HVDC) losses.
- Expansion of the datasets to include less common cable and transformer manufacturers
- Dynamic ratings of cables to increase the current carrying capacity
- Expansion of tool to model other renewable generation (Hydro, Wave)

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